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USE OF ELECTRICAL GEOPHYSICAL METHODS IN GROUNDWATER SUPPLY

By

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Use of Electrical Geophysical Methods In Groundwater Supply*

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INTRODUCTION

Both industrial and public water supplies benefit by technological procedures that aid in economically developing and maintaining adequate volumes of water of a sanitary quality. To so aid the waterworks of Illinois, the Illinois State Geological Survey has for many years carried on research and rendered service to the municipalities and industries of the State on the geological and geophysical aspects of groundwater supply. Other state agencies also render water supply services, the State Water Survey doing work on surface water supplies, stream-gaging in cooperation with the U. S. Geological Survey, pumpage of groundwater, and the chemistry of water, and the Department of Public Health handling all health and sanitation aspects. The work of these agencies is coordinated so that all inquiries are referred to the proper office for the assistance needed, with the result that in most cases joint reports are prepared by two of the agencies, and often the opinions of all three are applied to particular problems.

A major part of the work of the Geological Survey has been in the location of water-bearing deposits for development. This is done by preparation of reports for localities where adequate geological data are available. Where only meager data are available and the most likely source of suitable groundwater is a sand or gravel deposit in the glacial drift above the consolidated bedrock, surface geophysical surveys have been run by the electrical earth-resistivity method to guide test-drilling.

Another phase of the Survey's work has been the application of fundamental geological research done with oil-field electrical well-logging equipment to determine the producing conditions and the relative importance of the various bedrock aquifers in the northern portion of the state where deep wells are the chief source of groundwater supply. This work has lead to the recognition of the utility of electrical logging methods for obtaining accurate data on the conditions within wells to guide their operation, maintenance, and repair. This "geophysical logging" has become widely used in Illinois, and in addition to providing the solution to economic rehabilitation of many wells has given much data on water resources and well behavior.

This discussion outlines the methods and use of both electrical earth-resistivity surveys and geophysical well logging as done in Illinois. The work

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here described represents the joint efforts of several members of the staff of the Subsurface Division and of the Groundwater Geology and Geophysical Exploration Division who have contributed through the years to the successful operation of the electrical techniques. In addition, this work has been greatly aided by the excellent cooperation of the oil-field logging companies that operate in Illinois, the Halliburton Oil Well Cementing Company and the Schlumberger Well Surveying Corporation.

ELECTRICAL EARTH-RESISTIVITY SURVEYS

Field Procedure

The earth-resistivity surveys are conducted by a single operator for whom four assistants set electrodes. The assistants are provided by the organization (industry, municipality, public agency) for whom the survey is run. The instruments are portable where inaccessible places must be surveyed but are normally operated from the trunk of an ordinary passenger car along roads (Fig. 1).

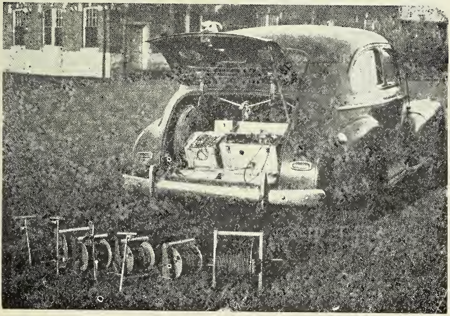

Figure 1—Resistivity instrument in rear trunk of car. Batteries are self contained, but at stations along roads where instrument is operated in the car the larger battery pack to the left is used.

The surveys can not be run where there are water mains, high voltage electric lines, any types of buried pipes or other materials that will greatly disturb the natural electrical fields or the natural resistance of the earth materials. Methods ordinarily used in Illinois can be used for prospecting only to depths of about 300 feet, but there is little need for prospecting to greater depths because only at a very few localities does the thickness of glacial drift exceed this amount.

It is important to know as much as

possible about local geological conditions before running a survey, so as to vary procedures to suit conditions met in the field. Analysis of all well data and mapping of the bedrock surface of a particular area usually indicate the distribution of preglacial valleys and aid in delineating areas for intensive work. Also available data on the surface geology frequently indicate areas where it is unlikely that water-bearing sands and gravels will be present. Because the measurements obtained from the electrical earth-resistivity survey are indirect, it is of paramount importance to obtain all available data that will aid in their detailed analysis and interpretation.

In actual operation, four electrodes

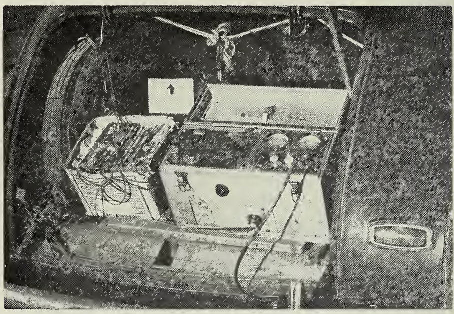

Figure 2—Resistivity instrument connected to electrodes through reels of wire used in field operation. The large reel of 4-conductor wire to the right is used to connect the large battery power supply with the instrument or the instrument with the electrode lines where stations are set up at distances up to 1,000 feet from the car.

are used, two of steel and two of copper (Fig. 2). The four elctrodes are arranged in a line at equal spacing with the instrument in the center and the two steel electrodes at the outside. The current is passed between the steel electrodes, and the potential drop is measured between the two inside copper electrodes. After a correction is made for commutator variation this reading is recorded in ohm-centimeters as the resistivity for that electrode spacing. The spacing of the electrodes, although not exactly indicative, is closely related to the depth to which the earth materials are affecting the resistivity value obtained. By setting the electrodes at successively closer spacings, successively shallower readings can be taken. Normally no readings are taken to depths that would be much below the top of bedrock because only the glacial aquifers are under investigation.

Interpretation of Earth-Resistivity Data

In general water-bearing sands and gravels in the glacial drift have higher resistivities than non-water-bearing clays and silts. However, the amount of fine clay or silt present in a sand or gravel will affect its resistivity. If a sand or gravel body contains water with any appreciable percentage of electrolyte, as has been found in a few cases, its resistivity will be affected. In addition, the thickness of the higher resistivity material and the thickness of any overlying lower resistivity material appreciably affect the value that may be obtained on the surface. Where adequate investigation has been made it is sometimes possible to assign an arbitrary value at a certain depth of electrode spacing, as indicative of the limit of good waterbearing permeable sand or gravel. For example, in some areas it has become obvious from experience that where the 80-foot reading is below 5,000 ohm-centimeters, no water-bearing sand and gravel in any appreciable thickness is present; elsewhere 7,000 ohm-centimeters in the 60-foot reading would be similarly indicative; other surveys have found highly permeable water-bearing gravel with the maximum value obtained as 4,400 ohm-centimeters at the 140-foot reading. Thus no general rule is drawn for the interpretation of resistivity data. A recent aid to the interpretation of these data has been the running of electric logs of test holes that penetrate the glacial drift to obtain a measurement of the resistivity of the materials in

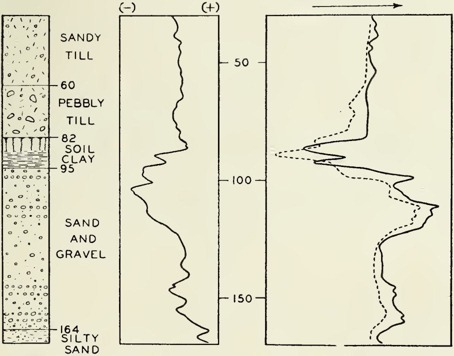

Figure 3—Electric log and sample log of rotary test-hole entirely in the glacial drift. The resistivity curve to the right, when correlated with the surface resistivity data, is a great aid in interpretation.

place (Fig. 3). These data can be integrated with readings at the surface and known geological data, and as a result a much more accurate interpretation is possible.

Such logs are not generally available on most of the surveys run. Fortunately the majority of areas surveyed have benefited from the long collection of data by the Geological Survey so that geological conditions are fairly well known and interpretations are reasonably simple. Usually the approximate position of the top of bedrock is known, and generally some data are available on its character and therefore its probable resistivity. In most cases it is thus possible to determine which readings represent high resistivity sandstones or limestones in the bedrock. The remaining high resistivity values (above 6,000-7,000 ohm. centimeters) are interpreted as representing clean sand or gravel above the bedrock. Such areas are readily outlined by setting a network of resistivity stations, and if a sufficiently large deposit is indicated, test-drilling is usually recommended.

The areas involving problems of interpretation are in the minority. In some portions of the state, gravels are present immediately above high resistivity limestone or dolomite bedrock, and it is extremely difficult to differentiate between the two materials from the surface readings. However, by use of special graphical interpretive procedures, all available well data, and appropriate precautions in interpretations, it has been possible to operate successfully in such areas (Fig. 4). The requests for surveys in

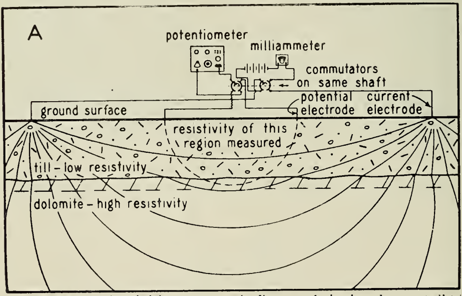

Figure 4—Earth-resistivity surveys. A: diagram of circuit and current distribution.

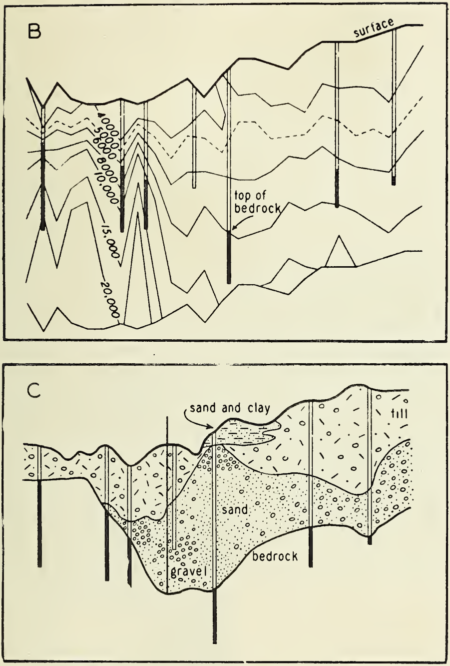

Figure 4—Earth resistivity surveys. B; graphic profile of earth resistivity along a traverse, bedrock penetrated in wells is shown in black; C; geological cross-section along traverse in B, based on interpretation of resistivity data and well records.

such areas are relatively infrequent because the dolomite bedrock is usually water-bearing, and typically the bedrock has been developed rather than the glacial drift aquifers. In some places salty water in the glacial drift has affected the resistivity data and their geological interpretations, although the low resistivity values clearly showed the undesirability for testing in the area. In some regions water-laid clays and silts of low resistivity so mask the electrical effect of thin but usable water-bearing gravels that satisfactory interpretations are not made unless this condition is recognized in the analysis of the data. Areas where borderline resistivity values are obtained (intermediate between what would be called low and high values, 4,000 to 6,000) also are difficult to interpret unless the cause for the results obtained can be recognized from geological data. Usually in such cases it is well to test-drill and to run an electric log to aid in interpreting the resistivity data.

Results of Resistivity Surveys

During the past fifteen years more than 200 surveys, ranging from just a few stations to nearly 1,000 stations, have been run in Illinois. Most of these surveys have lead to successful development of water supplies in the glacial drift or have had their results corroborated by test-drilling. In the comparatively few failures encountered further detailed study has indicated a reasonable explanation for the data obtained and has lead to recognition of some of the factors outlined above, that may affect correct interpretations.

The use of the resistivity method does not eliminate the need for test-drilling to guide development. However, through the years the use of the method has greatly reduced the number of exploration holes that need be drilled and has reduced the need for the exhaustive exploration that is necessary in some areas before development can take place. Test-drilling is necessary in order to obtain samples of the formation to be developed, samples of the water, and the data on the water levels, and to get a picture of the subsurface conditions that affect well development. After test-drilling it is desirable to reconsider the resistivity data in order to analyze the conditions. Many water supplies have been developed in Illinois after drilling a single test-hole on a site recommended on the basis of the resistivity survey. For large municipal or industrial supplies this is not advisable or possible, and the recommendations accompanying the resistivity report are based on the requirements of the organization.

GEOPHYSICAL LOGGING

Procedure

Most of the geophysical well logs in Illinois have been run by the commercial logging companies which operate in the oil fields (Fig. 5). They

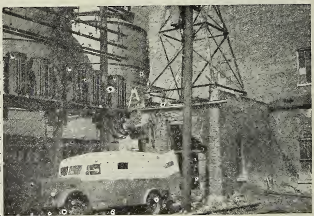

Figure 5—Geological logging truck in operation on a typical industrial well in northern Illinois.

are generally run with observers from the Geological Survey present to record data so that in the preparation and interpretation of the final log all pertinent information is available to the Survey staff. The expense of such logs is borne by the industries, municipalities, contractors, or other well owners, and all financial arrangements are made directly with the logging companies. Upon completion of the log all of the information obtained is analyzed by the Geological Survey and a report is prepared. An accompanying report on chemical and production data is prepared by the State Water Survey, and the joint reports are transmitted to the interested parties.

Most of the industrial and municipal wells logged are from 1,000 to 2,200 feet deep. For very shallow wells where the expense of commercial logging cannot be justified and where geophysical data are needed by the Geological Survey for research purposes, some logging is done with Survey equipment mounted in the Survey field laboratory truck (Figs. 6 and 7). At many wells logged since

Figuse 6—Geological Survey Field laboratory truck.

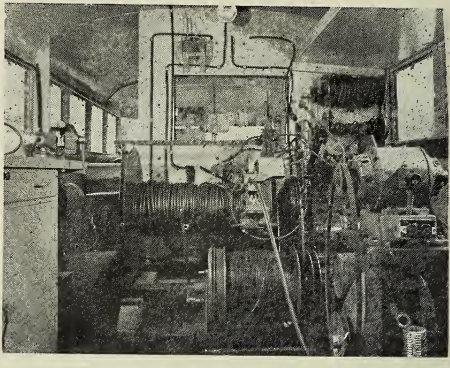

Figure 7—Rear view of Field Laboratory truck showing generators, measuring line, logging cable, and other equipment.

the completion of this truck early in 1945, the truck has been used in connection with the commercial logging equipment to provide facilities and working space for drafting and interpretation of logs, to use equipment not ordinarily available on the commercial logging trucks, and to provide auxiliary data and parameters of measurement not available from the commercial services.

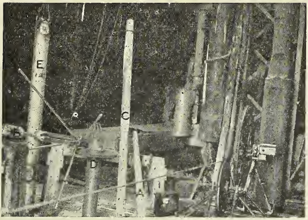

Figure 8—Some of the tools and devices used in making geophysical logs. A: Electric logging electrode for potential and impedance surveys; B: Hole caliper; C: Well-surveying temperature electrode; D: Current meter; E: Salter; F: Two-way speaker which is connected with the recorder cab in the logging truck.

From the geophysical logging trucks, various instruments (Fig. 8) are run into the wells to obtain the different types of data needed. Potential logs indicative of porosity and permeability, and resistivity or impedance logs, indicative of the character of the wall and the presence or absence of casing, together make an "electric log" which comprises the basic data of the geophysical log.[1] Any number of several other different types of logs may be run in any well. These include surveys of hole diameter, the resistivity of the fluid in the well bore, the temperature and current meter surveys to determine the direction and rate of movement of fluid in the well bore. Only rarely are all such surveys run, because most of the important problems and conditions can usually be determined from a few such logs. In some wells, however, in order to obtain full information it is necessary to run additional logs under special conditions, such as the addition of salt to the well fluid, or the raising of the fluid level or changing of the temperature of the fluid in the well by running in water from the surface.

All types of logs are made as continuous curves indicating the various electrical measurements and are usually recorded on film or paper. Be-

[1] For fuller explanation refer to Bays and Folk, "Developments in the application of geophysics to groundwater problems," **Proceedings Fourth Annual Water Conference, Engineers Society of Western Pennsylvania**; reprinted as **Illinois State Geological Survey Circular 108,** or Bays and Folk, "Geophysical Logging of Water Wells in Illinois," **Bulletin Western Society of Engineers,** Vol. 49, No. 3, September 1944; reprinted as **Illinois State Geological Survey Circular 113.**

cause of the importance of obtaining extremely accurate depth measurements in well work, very carefully calibrated measuring devices are used to drive the recording cameras (Fig. 9).

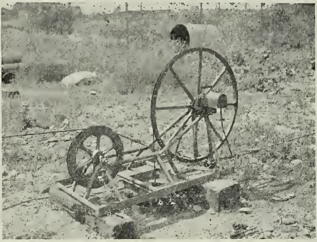

Figure 9—Measuring sheave and logging cable in operation. The counter and selsyn transmitter are geared to the large sheave and connected by cable with the camera in the logging truck.

All of the logs obtained from a well by geophysical methods and all of the available geological data from the well are integrated and drafted to make a composite geophysical log (Fig. 10).

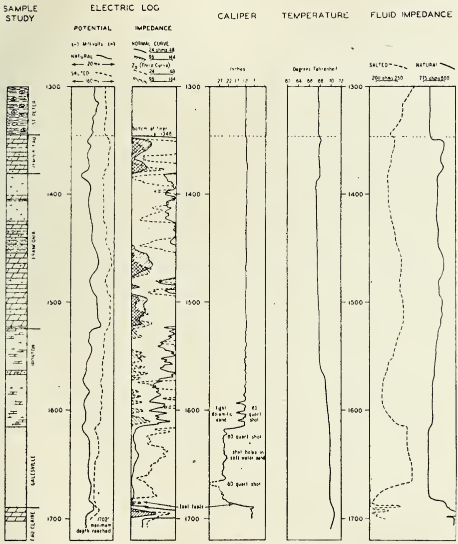

Figure 10—*Portion of a composite geophysical log of an ordnance plant well in northern Illinois showing effect of shooting, location of bottom of liner, lost tools, and other data on the well.*

Interpretation

From the data obtained by geophysical logging, various interpretations as to conditions within the well are made. The composite logs made by the Illinois Geological Survey present the basic data from which the following can be read or deduced:

1. A detailed log of the lithology of the uncased portion of well based on microscopic study.

2. Exact measurements of the casing and liners, both as to depths and inside diameters, and some knowledge of their condition.

3. Location, thickness, and relative importance of the water-producing zones and thereby the zones meriting rehabilitation or development.

4. Location of "thieving" zones.

5. Approximate salinity of the water in the well bore, and probable zones of production of waters of different salinities.

6. Temperature of the water in the well bore and the approximate temperature of water from different zones.

7. Caving zones that have not been cased off.

8. Circulation conditions under nonoperating conditions.

9. Critical production or well conditions such as collapsed or corroded liners, poor casing seats, location of iron or steel "fish," etc.

10. Effects of shooting, acidizing, caving, and other special conditions within the well.

The more basic data that are available in terms of accurate records during drilling and operation of the well, the more sure are the interpretations made from the geophysical log, or in many instances, the fewer are the curves that are needed to obtain conclusive answers to problems.

Results of Geophysical Logging

The many logs run in Illinois to date have been made for a number of different purposes among which are the following:

1. To obtain a correct log of the well where no record is available.

2. To pick the zone for development by shooting.

3. To accomplish research objectives.

4. To determine suitability for rehabilitation.

5. To obtain data on obstructions to lowering the pump.

6. To verify the recorded position of casing and liners and to obtain data on the condition of the casing and liners without pulling them.

7. To check the effectiveness of the casing seat and identify the probable source of polluted or contaminated water.

8. To obtain a permanent comprehensive record of a new well and verify its meeting specifications before acceptance.

9. To locate "fish" and the position of other metallic equipment in the well.

10. To determine cause of caving and best method of stopping caving or bridging of the hole.

11. To obtain all basic information to completely guide rehabilitation and repair work on old well.

Only rarely since geophysical logging passed the purely experimental stage has it been necessary to record more than three or four curves on any particular well in order to determine the answer to problems of the above type. Typical geophysical logs include an electric log, a caliper log, and a temperature log, and from the experience and knowledge obtained by previous work, much detailed information can be inferred from just these logs.

Typical deep-well water supply installations in northern Illinois represent many thousands of dollars in investments. For their maintenance, repair, and rehabilitation geophysical logging has been a rapid, inexpensive, and positive method of solving many of the problems involved. Because of the data thus made available, much higher well efficiencies have been obtained. Large increases in capacity have resulted in wells where the information for development of capacity was obtained from geophysical logs. Useless, contaminated, or polluted wells have been reconditioned and returned to useful operation. It has been found that the recognition of the best zone for shooting in one of the deep sandstone aquifers is more certain by electric-logging methods than by sample examination or any other known method. The low cost of rehabilitation of wells because of the knowledge obtained from geophysical logs has meant many dollars saved. In nearly every case, geophysical logging has given information which has permitted economies that have resulted in savings greater than the cost of logging; in many cases the savings effected by proper well repair have been many times the cost of the logging.

SUMMARY

The use of electrical geophysical methods in connection with ground-water supply work in Illinois has resulted in many benefits to municipalities, industries, and other well owners. The location of groundwater supplies in the glacial drift by the earth-resistivity method has greatly reduced the amount of test-drilling necessary for proper exploration and has permitted the location of many supplies that would not have been found otherwise by ordinary methods. Geophysical logging of wells has given much new data on wells in the state and has given a basis for greater effectiveness and less cost in the wells surveyed. All of the data obtained by these methods are by indirect electrical parameters of measurement, and appropriate caution combined with adequate geological and geophysical knowledge and experience are needed to make consistently sound interpretations.